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(12) # EUROPEAN PATENT APPLICATION

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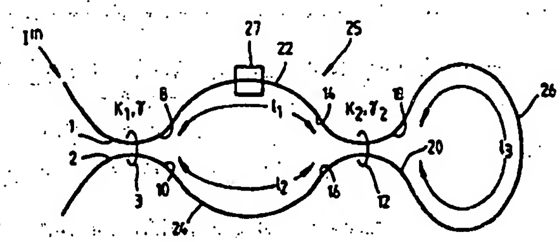
(54) **Interferometer.**

(57) An an all optical fibre interferometer is formed from an optical fibre Mach-Zehnder interferometer (25) whose output ports (18,20) are coupled by an optical fibre loop (20) which relaunches any optical signal output from either of the output ports (18,20) into a respective one of the output ports (20,18). A piezo-electric stretcher 26 is used to adjust the length of the arm (22) relative to the other arm (24) in response to a measurand. The interferometer outputs at port 1 an intereference signal dependant on the relative optical path length ofthe arms (22,24) allowing a measurand to be monitored via the same port 1 as the input optical signal I^{in} is coupled. This allows remote sensing via a single optical fibre coupled to port 1. The interferometer also finds application as a reflection modulator as a variable reflectivity mirror and Q-switch for a fibre laser.

Fig. 1.



EP 0 376 449 A1

INTERFEROMETER

This invention relates to interferometers.

One well known interferometer is the Mach-Zehnder interferometer in which an optical splitter splits an optical singal into two portions which propagate along distinct optical paths to an optical combiner. The relative phase difference between the two portions at the combiner can be monitored by allowing them to interfere and measuring the intensity of the resultant optical signal. The relative phase difference depends on the difference between the two optical path lengths. Such an interferometer can be used as a sensor or as a modulator by including means for altering the difference in optical path length between the two arms in response to a change in a measurand or modulating signal. An example is disclosed in a review article entitled "Optical Fibre Sensor Technology," IEE Transactions on Microwave Theory and Techniques Vol MTT-30 No.4 April 1982 pp473 - 480 by Giallorenzi et al.

A disadvantage of known Mach-Zehnder interferometers when used as sensors is that the interfering portions have to be monitored at an output port which is seperated from the input port. If it is necessary to monitor the condition of interferometer from a distance an optical waveguide, for example an optical fibre, needs to be coupled to the output to allow propagation of the optical portions back to the monitor. This can involve large amounts of fibre if the sensor is positioned remotely.

In this specification the term "optical" is intended to refer to that part of the electromagnetic spectrum which is generally known as the visible region together with those parts of the infra-red and ultraviolet regions at each end of the visible region which are capable for example of being transmitted by dielectric optical waveguides such as optical fibres.

According to the present invention an interferometer comprises an optical splitter having at least one input port and two optical splitter output ports; an optical combiner having two optical combiner input ports and two outputs ports; a first and a second optical arm each optically coupling a respective one of optical splitter output ports with one of the optical combiner input ports; and an adjustment means for changing the optical path length of one arm relative to the other; characterised in including relaunching means for relaunching any optical signal output from either of the combiner output ports into a respective one of the combiner output ports.

The signals exiting the combiner output ports which are produced as a result of an input signal being launched into an input port of the optical splitter (as in known Mach-Zehnder interferometers) will be relaunched into the optical combiner output ports and will thereby undergo a second transit through the Mach-Zehnder portion of the interferometer.

The optical splitter now acts as an optical combiner for the optical signals that have propagated back along the interferometer arms. These signals interfere. As will be explained in more detail later the resultant interference signal changes with the relative optical path length of the two arms but in this case the interference signal leaves the interferometer from the input port into which the original input optical signal was coupled can be monitored.

The reflected signal can therefore propagate back to the monitor station along the same optical waveguide which supplies the optical signal to the optical splitter. That part of the signal emerging from the input port into which the input signal was launched is by convention termed the reflected signal, and that emerging from the other input port if there is one (for example when the splitter is a four port fused fibre coupler) is termed the transmitted signal.

The Mach-Zehnder portion of the interferometer may be formed from bulk optic components comprising a first and a second beam splitter, and a first and a second mirror in known manner. Light entering the device is split into a first and a second portion by the first beam splitter. The portions each follow a separate optical path to the optical combiner, for example one defined by the first and second mirror respectively, the other being a straight optical path, where they recombine to produce first and second output interference signals at a first and second output port.

The relaunching means of the present invention used with such a bulk optic Mach-Zehnder interferometer may comprise two mirrors positioned such that the output signal from the first output port of the Mach-Zehnder interferometer is incident on a third mirror, and then on a fourth mirror and finally is relaunched into the Mach-Zehnder interferometer via the second input port. An output signal from the second input port will be incident on first the second mirror and then onthe first mirror to be relaunched into the Mach-Zehnder interferometer via the first input port. Alternatively the third and fourth mirrors may be arranged to relaunch light from each output back into the same output.

A particularly convenient form of the interferometer is formed by a pair of 4-port optical couplers optically coupled by a pair of optical waveguides,

for example optical fibres, which constitute the optical arms, the means for relaunching comprising a looped optical waveguide formed between the first and second output ports of the Mach-Zehnder Interferometer. Such a device may be formed from a single length of fibre, is robust and does not suffer from any of the alignment problems which would be incurred if the device were made either entirely, or partially from bulk optics.

The present invention may also be formed from planar waveguides, for example formed in a $LiNbO_3$ substrate. In such an embodiment the optical splitter may have a single input.

The device is employable as a sensor by arranging for the adjustment means to be sensitive to the quantity to be measured, for example by mechanical stretching due to incident vibrations or by an electro-optical effect.

It will be appreciated that the invention is applicable to Mach-Zehnder interferometers in general and is not limited to specific types of splitters, combiners or relaunching means nor specific adjustment means for changing the optical path length of one arm relative to the other that may be mentioned by way of specific example.

The present invention can find applications other than as a sensor by using of the property that the reflected signal can be modulated by the adjustment means. For example, the interferometer can be used as a variable output reflector for, or to provide Q-switched operation of a fibre laser.

Embodiments of the invention will now be described by way of example only with reference to the following diagrams in which:

Figure 1 is a schematic representation of an optical fibre interferometer according to the present invention;

Figure 2 is a schematic representation of a bulk optical interferometer according to the present invention;

Figure 3 is a schematic representation of an experimental arrangement used to characterise the embodiment of Figure 1;

Figure 4 is a graph of transmitted and reflected output intensity of the embodiment of Figure 3; and

Figure 5 is a schematic representation of a fibre laser having an interferometer according to the present invention as one of the laser mirrors.

Referring to Figure 1 an optical fibre interferometer comprises an optical splitter 3 having input ports 1 and 2 and optical splitter output ports 8 and 10, an optical combiner 12 having optical combiner input ports 14 and 16 and output ports 18 and 20, the pairs of ports 8 and 14, and 10 and 16 being optically coupled by arms 22 and 24 respectively to form a Mach-Zehnder Interferometer 25, and ports 18 and 20 coupled by the loop 26 constituting the relaunching means. The device was formed from a single, single-mode optical fibre, the splitter 3 and combiner 12 being fused tapered couplers made in known manner. Other couplers may be employed, for example polished optical couplers or optical waveguide couplers if the invention is implemented for example in a $LiNbO_3$ substrate.

A piezo-electric stretcher 27 can be actuated to change the optical path length of one arm 22 relative to the other 24. Other devices capable of so changing the relative optical path length of the arms 22 and 24 may be used instead.

Referring to Figure 2, the bulk optics equivalent to figure 1 is shown, equivalent features being indicated by the same numerals primed. An optical splitter and combiner 3′, 12′ are formed by half mirror beam splitters, the arms 22′ and 24′ being defined by full mirrors 22′A and 24′A and loop 26′ by full mirrors 26′A and 28′B. The optical path length is adjustable by means of the movable prism 28′.

A methodology for setting up equations to describe optical fibre interferometers of arbitrary complexity, which involve directional couplers, has been described in an article by P.Urquhart, Applied Optics Vol 26 (1987) 456. Using this approach, a set of linear equations can be set up which establishes the relationships between the components of the complex electric field propagating in both directions at the points of the device which are immediately adjacent to the couplers. There are as many equations as there are unknown quantities, which in the present case is sixteen. This formalism gives the same results as the method which relies on summation of field components which describe the various pathways through the structure but is more suitable for use with complicated structures. In analysing the interferometer of the present invention it is assumed that the state of polarisation remains constant throughout the device. In practice it was found that polarisation control was necessary. This can be achieved by any one of the following: (a) appropriate adjustment of the lie of the optical fibre, (b) using polarisation controllers, c) using polarising maintaining fibres and polarisation couplers.

It is assumed K_i and γ_i are the intensity coupling ratio and the coupling loss respectively, of the splitter 2 and combiner 12, where $i = 1$ or 2 for the fibre couplers constituting the splitter and combiner respectively. The lengths of the arms 22 and 24 and loop 20 are l_1, l_2 and l_3. The (field) loss and propagation constant are α and β, respectively. β is given by

$$\beta = 2\pi n_e/\lambda \quad (1)$$

where n_e is the effective fibre refractive index and λ is the free space wavelength.

When solved simultaneously the initial equations give solutions for the outputs at ports 1 and 2. The field solutions are multiplied by their own complex conjugates to give two corresponding output intensities. These can be described by a single equation in which the constants take on one of two forms, depending on which output port is being considered. The intensity response function may be expressed as

$$I_i^{out}/I_i^{in} = [(A_i + B_i + C_i)^2 - 4A_i(B_i + C_i)\sin^2(\delta/2) - 4B_iC_i\sin^2(\delta)]\exp(-2\alpha l_3), \quad (2)$$

where δ is the phase difference between the two arms of lengths l_1 and l_2, and is given by

$$\delta = \beta(l_1 - l_2). \quad (3)$$

The constants are given by A_i, B_i and C_i in which $i = 1, 2$ depending upon whether the output is from port 1 or 2.

$$A_1 = r_1t_1 \exp(-\alpha(l_1 + l_2)) \quad (4)$$
$$B_1 = r_2 (1-K_1)(1-\gamma_1) \exp(-2\alpha l_1) \quad (5)$$
$$C_1 = -(r_2K_1)(1-\gamma_1) \exp(-2\alpha l_2) \quad (6)$$
$$A_2 = t_1t_2\exp(-\alpha(l_1 + l_2)), \quad (7)$$
$$B_2 = -r_1r_2\exp(-2\alpha l_1)/2 \quad (8)$$
$$C_2 = r_1r_2\exp(-2\alpha l_2)/2 \quad (9)$$

The amplitude transmissivity and reflectivity terms that would apply to a loop reflector made from zero loss fibre with coupling ratio K_i and coupling loss γ_i have been identified in the analysis and are given by r_i and t_i, respectively. These terms are given by the following equations:

$$r_i = 2K_i^{1/2}(1-K_i)^{1/2}(1-\gamma_i), \quad (10)$$
$$t_i = (1-2K_i)(1-\gamma_i). \quad (11)$$

When the optical path lengths of the arms l_1 and l_2 are equal, δ is zero and equation (2) becomes

$$I_i^{out}/I_i^{in} = (A_i + B_i + C_i)^2\exp(-2\alpha l_3). \quad (12)$$

Equation (12) is an invariant function with respect to δ; that is light is merely split unequally between the two ports. The device is then showing loop reflector characteristics.

Consider now that both couplers have coupling ratios of 1/2. The output then takes on the following simple form.

$$I_i^{out}/I_i^{in} = [(B_i + C_i)^2 - 4B_iC_i\sin^2(\delta)]\exp(-2\alpha l_3) \quad (13)$$

It is noteworthy that t_i has a small value even when K is approximately, but not exactly, equal to 1/2. It can thus be seen from equations (4) and (7) that A_1 and A_2 are approximately zero. Consequently, we would expect that equation (13) would apply to a good approximation even when the couplers do not have a splitting ratio of exactly 50:50. Such insensitivity to an important component value is to be seen as a desirable feature of the present invention. A further feature of equation (13) is that we can easily see the effect of losses in arms 22, 24 and loop 20, which could arise from making the device from splicing two couplers together in three positions. The length-loss products αl_i, which appear in equations (4) to (9) and (13) can be multiplied by an appropriate scaling factor. The discrete splice loss is thus replaced by an equivalent distributed loss in the arm of length l_i. As can be seen from the constants B_i and C_i in equation (13), the effect of splice losses is to bring about a small reduction in both the peak output intensity and the depth of modulation.

In the situation where the losses of the fibre and both couplers take on the low values of fractions of a dB, which are routinely achievable in practice the intensity equations can be written to a good approximation in the following form:

$$I_i^{out}/I_i^{in} = \sin^2(\delta),\ i = 1,\ = \cos^2(\delta),\ i = 2. \quad (14)$$

Equation (14) shows that, as required by conservation of energy, the sum of the outputs from the two ports is unity. It can also be seen from equation (14) that when low loss components are used in conjunction with 50:50 couplers, the light output from the two ports is determined only by the relative phase change, δ associated with the transits in the two arms. δ depends upon the difference in the optical path length of the two arms 22 and 24, $(l_1 - l_2)$ and on the propagation constant, β. Thus in order to bring about a variation in δ and hence a change in the output intensity of the two arms either β or $(l_1 - l_2)$ must be varied. There are several ways can be achieved in practice. The fibre may be stretched along its length or a temperature change made to one of the fibres. Alternatively, the wavelength of the light launched into the interferometer can be adjusted. The present invention is therefore useful as a sensor or reflection modulator.

The experimental arrangement used to examine the performance of the embodiment of the present invention shown in Figure 1 is illustrated in Figure 3, in which the entire device is made from standard single mode telecommunications-type optical fibre with fused-tapered couplers. Those elements in common with the Figure 1 embodiment are referenced by the same numerals. The technique adopted to scan the relative phase difference, δ, was to launch light of a constant wavelength into port 1 and to vary periodically the length of the fibre in arm 22 with the piezo-electric stretcher 27. Thus stretching the device applied a constant phase shift linearly related to an applied voltage ramp, which was in turn synchronised to the timebase of an oscilloscope (not shown). Time therefore becomes directly proportional to the phase difference, δ.

An InGaAsP external cavity semiconductor diode laser 30 which had a measured operating wavelength of 1.53374µm was used to provide the input signal. An optical isolator (not shown) prevented laser instabilities due to reflected signals. A third directional coupler 32 was spliced to the input port 1. The launched, transmitted and reflected signals were monitored by positioning detectors

D1-D3 at three locations connected to a high resolution oscilloscope (not shown). Values of the lengths l_1, l_2 and l_3 of the arms 22 and 24 and the loop 26 was 0.85m, 0.95m and 1.10m respectively. The fused couplers were designed to be 50:50 at 1550 nm. Their measured coupling ratios at the operating wavelength were $K_1 \approx K_2 = 0.52 \pm 0.01$. Both couplers had excess losses of about 0.05 to 0.1 dB. The coupler 32 had a splitting ratio of 0.55.

The experimentally measured transmitted and reflected output intensities from ports 2 and 1, respectively, are plotted as a function of relative phase change, δ, in figure 4. As can be seen, the traces correspond closely to the $\sin^2$ and $\cos^2$ responses required by equation (14). Four cycles of the curves are shown. Even when observation was made over a larger number of periods there was no evidence of the higher frequency, $\sin^2(\delta/2)$ component indicated in equation (2). This is to be expected because A_l, as given by equations (4) and (7), is small when $K_l \approx 1/2$. The peak values of the measured transmitted and reflected intensities were 0.53 I^{in} and 0.26 I^{in}, respectively, where I^{in} is the launched intensity from the laser. The reflected peak intensities are lower in magnitude as they had to pass through the input coupler twice before detection. The measured values compared well with the expected values of 0.55 I^{in} and 0.248 I^{in} for the transmitted and reflected signals, respectively. As can be seen from figure 4 there was a low level of unmodulated signal. The unmodulated throughput was measured to be no more than 0.026 I^{in}, indicating that despite the fact that couplers 3 and 12 were not exactly 50:50, a good depth of modulation could be achieved. As discussed above this is consistent with the expectation that the response should be reasonably insensitive to non-optical coupling ratios and the presence of small excess losses.

From the calculated variation of output power with respect to phase it has shown that a variety of output responses is possible. Two responses are of particular interest. When the two constituent arms are of equal optical length the device acts as frequency independent reflector. When both of the direction couplers have a coupling ratio of 50% the dependence of output power from the two ports on the relative phase difference, δ, of the signals in the two arms are given simply by $\sin^2(\delta)$ and $\cos^2(\delta)$. A relative phase variation can be brought about by a variety of means which means are well known in the art of Mach-Zehnder sensor technology, and modulation is thus possible over the full range of power levels. The experiment confirmed that by elongating one of the arms by a few microns the $\sin^2(\delta)$ and $\cos^2(\delta)$ response predicted by the calculations. An important strength of the present invention is that nearly full modulation is obtained even when non-optimal 50% couplers are used.

Because the reflection modulation depends on a relative phase difference between the two arms of the interferometer, the frequency of oscillation can be as great as the modulation of the phase in one arm. This is a significant advantage over a single optical fibre loop Sagnac reflector in which reflection modulation takes place by differential phase delays in the same (loop) path or in which the coupling ratio of the splitter is modulated to vary the reflected signal.

Referring now to figure 5, an optical fibre laser comprises known erbium doped silica optical fibre 34 which forms the active lasing material of a lasing cavity defined by a wavelength selective dichroic mirror 36 at one end of the fibre and a interferometer according to the present invention spliced to the other by fusion splice 38. It is pumped by the laser pump 40 in a known manner. A controller 42 is used to control the piezo-electro stretcher 27 which can thereby be set to vary the reflectivity of the interferometer (as regards an optical signal entering at port 1 from the fibre 34). The present invention is of course applicable to other laser arrangements including bulk optical lasers. It is known that the optimum output power of a laser depends on the reflectivity of its cavity mirrors. The present invention can be used as a variable reflectivity mirror to optimise the efficiency of the laser. The speed of change of the reflectivity also allows it to be used as a reflective modulator for Q-switching a laser.

The reflected and transmitted portions of the input optical signal vary periodically with frequency. The present application can therefore be used as a frequency filter, for example to select portions from a comb of frequencies.

Claims

1. An interferometer comprising -
an optical splitter having at least one input port and two optical splitter output ports;
an optical combiner having two optical combiner input ports and two output ports;
a first and a second optical arm each optically coupling a respective one of optical splitter output ports with one of the optical combiner input ports; and
an adjustment means for changing the optical path length of one arm relative to the other;
characterised in including relaunching means for relaunching any optical signal output from either of the output ports into a respective one of the output ports.

2. An interferometer as claimed in claim 1 in which the optical splitter and optical combiner are

optical waveguide couplers and the arms are optical waveguides.

3. An interferometer as claimed in claim 2 in which the relaunching means comprises an optical waveguide optically coupling the two optical combiner outputs.

4. An interferometer as claimed in claim 2 in which all the optical waveguides comprise optical fibres.

5. An interferometer as claimed in claim 4 in which all the waveguides are formed from a single optical fibre.

6. A laser having at least one end of lasing cavity defined by an intrerferometer as claimed in any preceding claim.

7. A laser as claimed in claim 6 in which the lasing cavity comprises an optical fibre lasing medium and the interferometer is an all fibre optical interferometer.

Fig. 1.

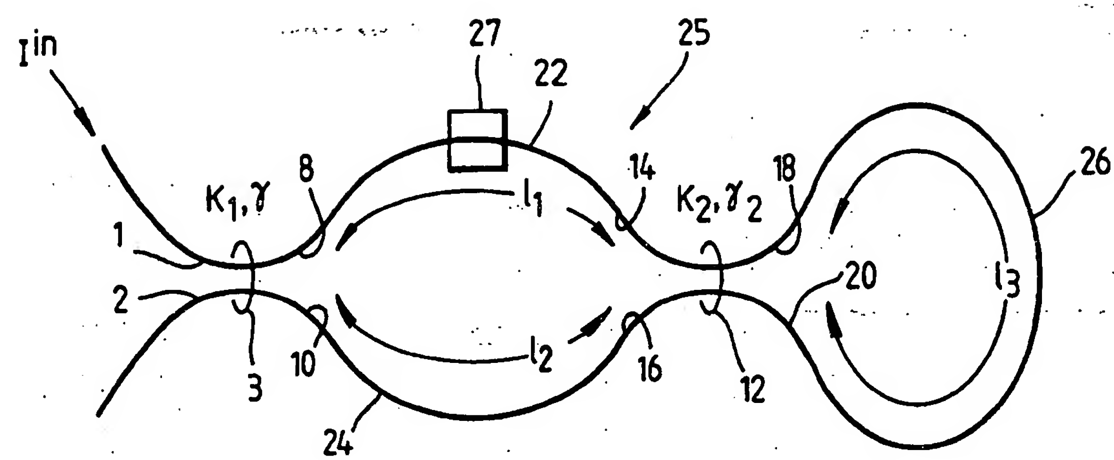
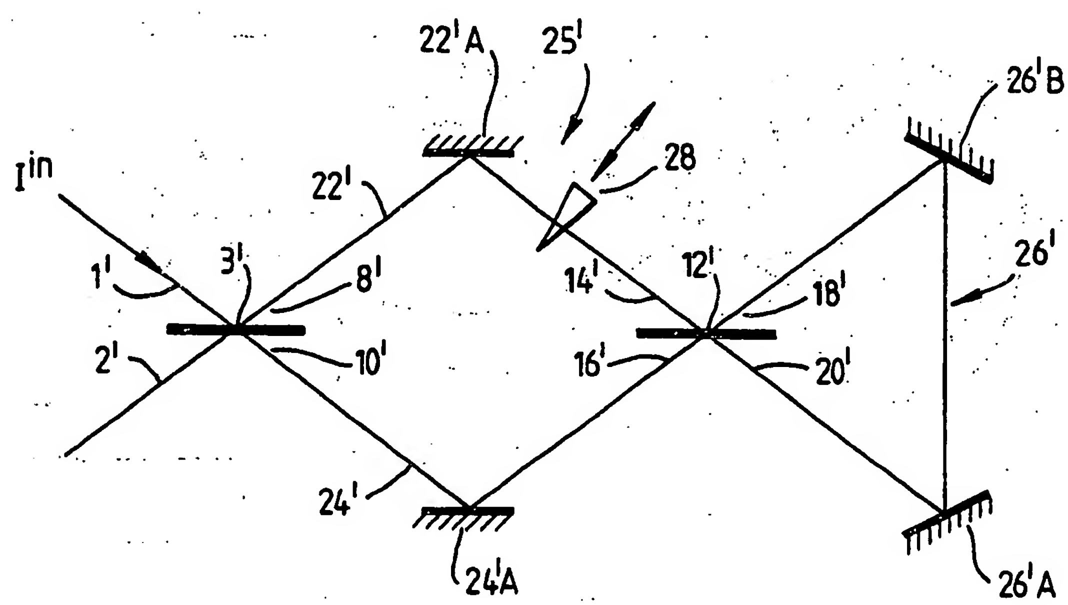

I in
27
22
25
K1,γ
8
14
K2,γ2
18
26
l1
1
2
20
l3
3
10
l2
16
12
24

Fig. 2.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25'
26'B
28
I in
22'
1'
3'
8'
14'
12'
18'
26'
2'
10'
16'
20'
24'
24'A
26'A

Fig. 3.

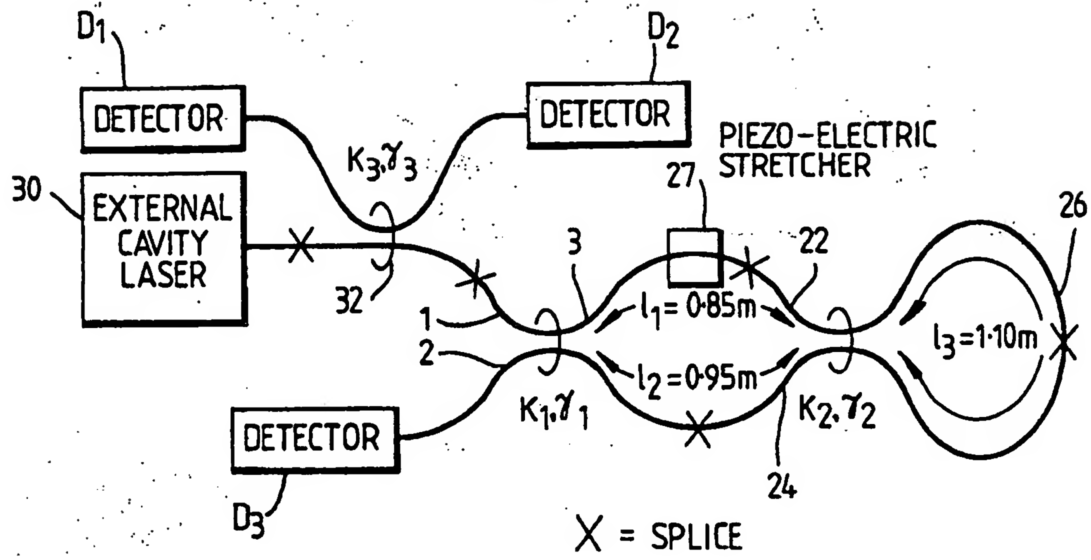
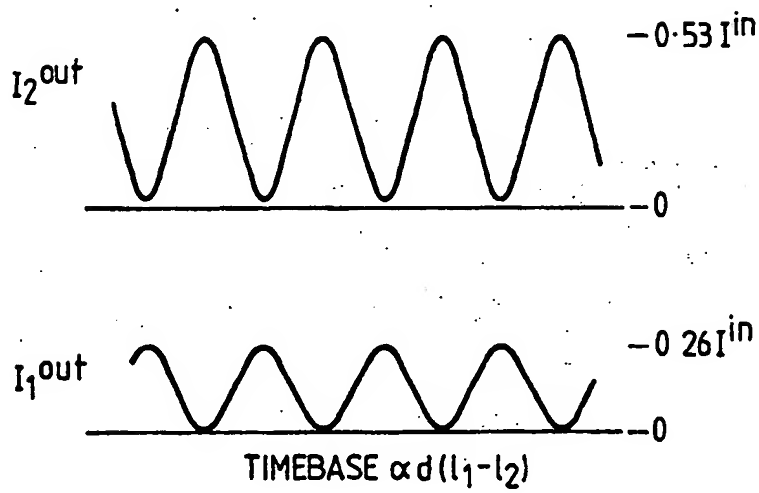

D1
DETECTOR
D2
DETECTOR
PIEZO-ELECTRIC
STRETCHER
27
K3,γ3
30
EXTERNAL
CAVITY
LASER
32
3
22
26
1
2
l1 = 0·85m
l2 = 0·95m
l3 = 1·10m
K1,γ1
K2,γ2
24
DETECTOR
D3
X = SPLICE

Fig. 4.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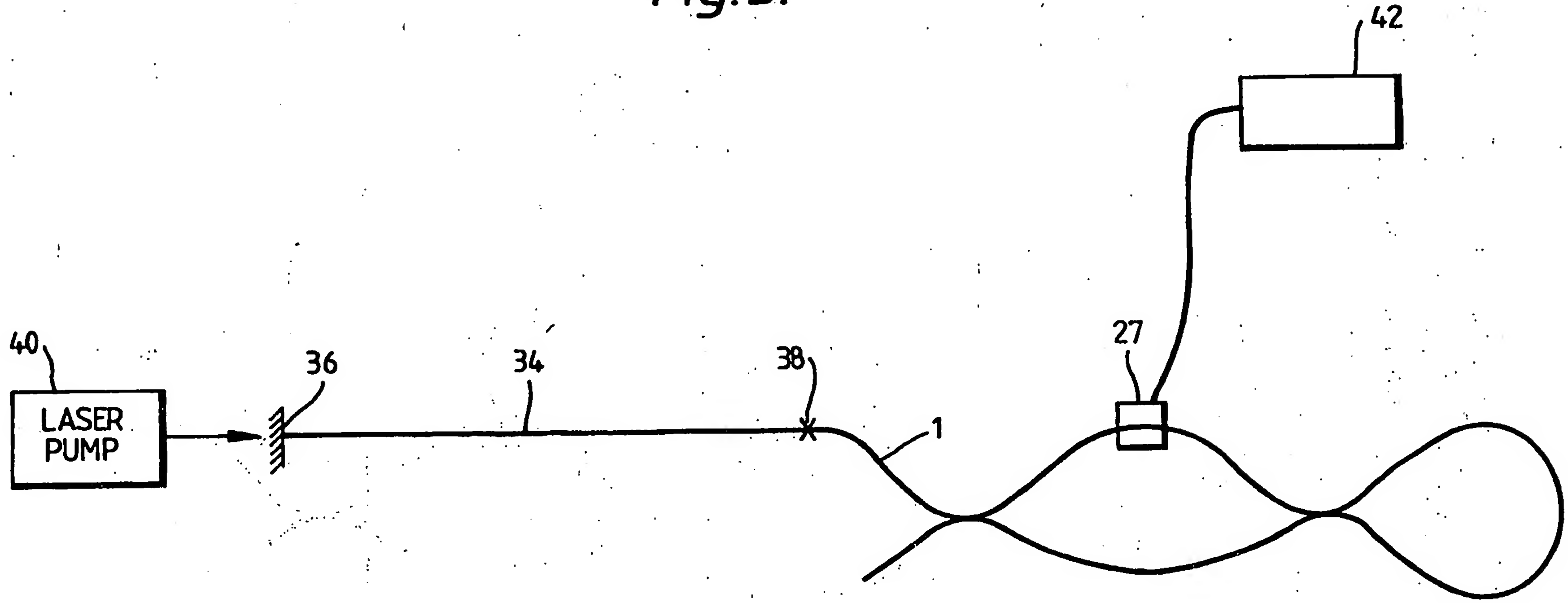
0·53 Iin
0
I1out
0 26Iin
0
TIMEBASE ∝ d(l1−l2)

Fig.5.



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EUROPEAN SEARCH REPORT

Application Number

EP 89 31 1299

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	DE-A-3 014 719 (LICENTIA) * Figures 1,2; page 4, lines 15-25 * ---	1,4	G 01 D 5/26 G 01 J 9/02 G 01 B 9/02 G 01 H 9/00 G 02 B 6/28 G 01 S 3/08
A	US-A-4 725 141 (G.A. GEORGIOU) * Figures 4,5; claim * ---	1,2,4	
A,D	IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-30, no. 4, April 1982, pages 472-511, New York, US; T.G. GIALLORENZI et al.: "Optical fiber sensor technology" * Figure 24 * ---	1-5	
A	OPTICS AND SPECTROSCOPY, vol. 58, no. 5, May 1985, pages 675-677, The Optical Society of America, Washington, US; L.V. IOGANSEN et al.: "Multimode fiber interferometers" * The whole article * ---	1-6	
A	US-A-4 753 529 (M.R. LAYTON) * Figures 1,17; column 10, lines 57-68; column 11, lines 1-22 * ---	1,2,4	**TECHNICAL FIELDS SEARCHED (Int. Cl.5)**
A	APPLIED PHYSICS LETTERS, vol. 41, no. 3, August 1982, pages 231-233, American Institute of Physics, New York, US; J.E. BOWERS: "Fiber-optical sensor for surface acoustic waves" * Figure 1; page 231, column 1, lines 1-41; column 2, lines 1-8 * --- -/-	1,2,4	G 01 D 5/26 G 01 B 9/02 G 01 J 9/02 G 01 H 9/00 G 02 B 6/00 H 01 S 3/00

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	06-02-1990	MATHYSSEK K.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	APPLIED OPTICS, vol. 27, no. 15, 1st August 1988, pages 3107-3113, Optical Society of America, New York, US; T.A. BIRKS et al.: "Jones calculus analysis of single-mode fiber Sagnac reflector" * Pages 1,2 *	1,3	
A	EP-A-0 247 882 (BRITISH TELECOM.) * Whole document *	1,3-7	
A	US-A-3 589 794 (E.A.J. MARCATILI) * Figures 4,21; column 3, lines 23-49; column 8, lines 42-70 *	1,2,3	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	06-02-1990	MATHYSSEK K.

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X : particularly relevant if taken alone
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O : non-written disclosure
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T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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(54) **Acoustic transducing arrangements and methods.**

(57) Systems and methods are disclosed which provide an electrically passive optically controlled acoustic transceiver system which measures the quantity of a liquid (20), such as aircraft fuel, in a tank (12). Pulsed electromagnetic radiation, such as light or infra-red radiation, is guided through an optical fibre (34) and impinged upon a flexible member (30) adapted to flex when heated and transmit acoustic pulses. An optical fibre detector (34,42) is used to monitor the acoustic pulses reflected from the liquid level (22) in the tank (12). The system is electrically passive and does not require or use electrical power at the sensing location.

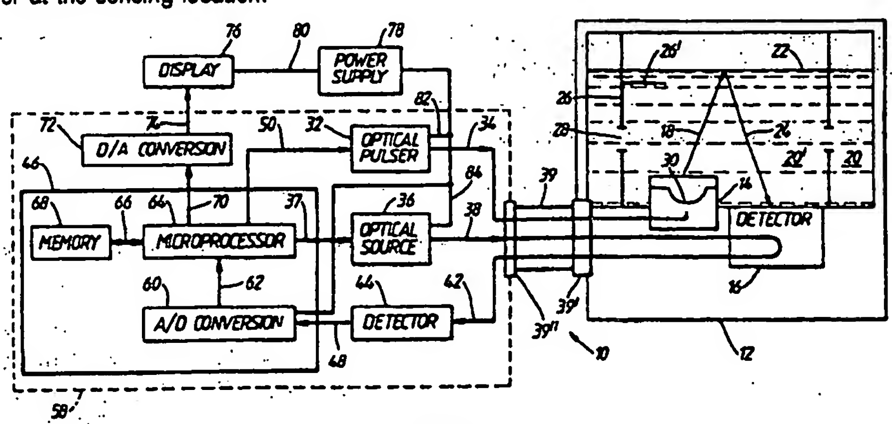

Fig.1.

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ACOUSTIC TRANSDUCING ARRANGEMENTS AND METHODS

BACKGROUND OF THE INVENTION

The invention relates to electro-acoustic transducing arrangements and methods. More particularly, the invention provides electrically passive acoustic transmission and detection for liquid quantity gauging. Embodiments of the invention are useful for fuel quantity gauging in aircraft fuel tanks.

US-PS-4 677 305 (Ellinger, assigned to Simmonds Precision Products, Inc.) discloses an opto-acoustic fuel quantity gauging system which uses an electrically activated transducer.

Brown, D.H., "Liquid Level Measurement by Ultrasonic Ranging", Central Electricity Generating Board (London, Aug. 1976), discloses the concept of an ultrasonic ranging device for measuring the liquid level in a container. An ultrasonic pulse is propagated upwardly from the bottom of the container. The propagation time between the generation of the pulse and the reception of the reflected wave is indicative of the liquid level. US-PS-4 580 448 (Skrgatic) discloses a system somewhat similar to that of Brown and which uses an ultrasonic liquid level sensor in which an ultrasonic crystal transducer mounted exteriorly of the liquid container transmits a pulse through the container wall and the liquid and detects the reflected wave to determine liquid level.

US-PS-4 334 321 (Edelman) discloses an opto-acoustic transducer by which power-modulated light is transmitted through a fibre and absorbed to generate heat which, in turn, effects expansion and contraction of the light guide to develop sound energy. The transducer is indicated as providing an audio output of between 300 and 3300 Hz.

EP-A-0 232 610 discloses a photothermal oscillator force sensor which includes a beam of silicon caused to resonate by impingement of light thereon.

SUMMARY OF THE INVENTION

According to the invention, there is provided an electro-acoustic transducing arrangement, comprising a movable member, and characterised by an input device directing electromagnetic energy into impingement on the movable member whereby to cause the member to move and emit acoustic energy, and an output device comprising a device carrying electromagnetic energy and subject to impingement thereon of the emitted acoustic energy whereby to cause modulation of the carried electromagnetic radiation.

According to the invention, there is also provided an optically controlled acoustic transmission and reception system, characterised by a tank, an electrically passive acoustic transmitter controlled by electromagnetic radiation, an acoustic receiver, a source of electromagnetic radiation, a first optical fibre, the first optical fibre being connected to transmit electromagnetic radiation from the source thereof to the transmitter which converts electromagnetic radiation into emitted acoustic energy, the transmitter being positioned to emit the acoustic energy into the tank, the acoustic receiver being positioned to receive the acoustic energy emitted by the transmitter and to produce a corresponding output.

According to the invention, there is further provided an acoustic transducing method, characterised by the steps of impinging electromagnetic radiation on an input movable member so as to cause the member to move and emit acoustic energy, and causing the emitted acoustic energy to impinge on an output movable member and thereby cause modulation of further electromagnetic energy.

According to the invention, there is still further provided a method of emitting acoustic waves into a liquid enclosed by a tank, characterised by the step of feeding electromagnetic radiation through an optical fibre into impingement on a flexible member mounted within the liquid so as to vibrate in response thereto and emit acoustic waves into the liquid.

In embodiments of the invention, an electrically passive optically controlled acoustic transceiver system measures the quantity of a liquid, such as aircraft fuel, in a tank. Pulsed electromagnetic radiation, such as light or infrared radiation, is guided through an optical fibre and impinged upon a flexible member adapted to flex when heated and transmit acoustic pulses. An optical fibre detector is used to monitor the acoustic pulses reflected from the liquid level in a fuel tank. The system is electrically passive and does not require or use electrical power at the sensing location.

DESCRIPTION OF THE DRAWINGS

Optically controlled acoustic transmission and detection systems and methods according to the invention for fuel quantity gauging will now be described, by way of example only, with reference

to the accompanying drawings, in which:-

Figure 1 is a schematic representation of one of the systems; and

Figure 2 is a schematic representation of another of the systems.

DESCRIPTION OF PREFERRED EMBODIMENTS

In an embodiment of the invention to be described in more detail, an electrically passive optically controlled acoustic transceiver system is provided which measures the quantity of a liquid, such as aircraft fuel, in a tank. Pulsed electromagnetic radiation, such as light or infrared radiation, is guided through an optical fibre and impinged upon a flexible member of an opto-acoustic transducer. The flexible member is adapted to flex when heated. The energy of each pulse of electro-magnetic radiation is rapidly absorbed as heat by the flexible member. Preferably, the flexible member is a thin semispherical shaped black-coated metal member supported to allow it to flex when heated by the pulses of electromagnetic radiation. Each flexing of the metal member initiates an acoustic pulse which is directed to travel through a liquid to an air-liquid interface from which a reflected acoustic pulse returns through the liquid to a monitoring optical fibre. The monitoring optical fibre directs light (or infrared radiation) to a detector. The travel time of each of the acoustic pulses to and from the liquid-air interface is measured by monitoring the time between initiating the acoustic pulse and detecting the return of the reflected acoustic pulse. The return of the reflected acoustic pulse is detected as a change in the properties of the transmitted light or infrared radiation.

With more particular reference to Figure 1, an electrically passive opto-acoustic liquid quantity gauging system 10 for an aircraft is shown. The electrically passive acoustic fuel quantity gauging system shown generally at 10 includes a tank 12 which supports an acoustic source 14 and an acoustic detector 16, and encloses liquid fuel 20. The source 14 transmits acoustic output pulses 18 through still fuel 20′ enclosed by stillwell 26 to the liquid-air interface 22 from which acoustic reflection pulses 24 are reflected to acoustic detector 16. The stillwell 26 is supported by the tank 12 so that the pulses 18 and 24 travel through still fuel 20′ which is less turbulent in flight than is the portion of fuel 20 which is outside of the stillwell 26. Stillwell 26 supports reference reflector 26′. Fuel flows freely into and out of the stillwell 26 through aperture 28.

The source 14 preferably includes a metal member 30 having a rounded or semispherical (concave or convex) shape supported to allow flexion of the rounded portion. Preferably, at least a portion of the surface of the metal member 30 is nonreflective and black. Optical pulser 32 pulses high intensity light through optical fibre 34 to the plate 30 which rapidly flexes thereby transmitting acoustic pulses 18. The pulser 32 is preferably a pulsed laser, pulsed laser diode, Q-switched laser or optically pumped Q-switched laser.

The optical source 36 transmits light through optical fibre 38 to acoustic detector 16. Reflected acoustic pulses 24 impinge upon detector 16. The detector 16 is preferably a loop 40 in optical fibre 38. The fibre 38 may be a single mode or multimode optical fibre. The output portion 42 of fibre 38 channels the light to optical detector 44. The optical fibre 34, 38 and 42 extend through connectors 38′ and 39″ and are protected by shielding 39. Detector 44 is connected to signal conditioning electronics 46 by electrical conductor 48. Signal conditioning electronics 46 is connected by electrical conductor 50 to the optical pulser 32.

Opto-acoustic signal conditioner 58 includes pulser source 36, detector 44 and signal conditioning electronics 46. Signal conditioning electronics 46 includes analog to digital (A/D) converter 60 which is connected by electrical conductor 48 to detector 44, and by electrical conductor 62 to microprocessor 64. Microprocessor 64 sends and receives signals from memory 68 through electrical conductor 66.

Microprocessor 64 sends digital signal through conductor 70 to D/A converter 72. D/A converter 72 sends analog signals through electrical conductor 74 to display 76. Power supply 78 supplies electrical power through electrical conductor 80 to display 76. Power supply 78 supplies electrical power through electrical conductor 82 to optical pulser 32. Electrical conductor 84 is connected to power supply 78 which supplies electrical power to optical source 36. Power supply 78 supplies electrical power through electrical conductor 86 to A/D converter 60 and to the other components of signal conditioner 58 through connections not shown.

By detecting and indicating changes in the light signal from the optical source 36, the return of the reflection pulses is detected and used to indicate the quantity of fuel in tank 12. The detector 44, which is preferably a photodetector, receives electromagnetic radiation, such as light, from the output portion 42 of optical fibre 38. It will be understood that any type of physical movement of the optical fibre 38, such as slight bending, in response to impact of the reflected acoustic pulses, will have an effect upon the light transmitted therethrough. Various parameters (or properties) of the light can be detected, such as back scattering sites, discontinuities, attenuation, and the like. The movement of the optical fibre caused by the impact

of the returning acoustic waves (reflection pulses) causes changes in the properties of the light signal travelling within the optical fibre. Such changes in the properties of the light in the output portion of optical fibre 42 form optical information which is converted to electrical digital form in A/D converter 60 and fed into the microprocessor 64. The fuel quantity in tank 12 is determined in microprocessor 64 and signals representative of fuel quantity are displayed by display 70. The microprocessor 64 may send further signals to the optical pulser 32 to control the starting time of the acoustic wave pulses 18.

In order to carry out the level measurement, it is necessary to know the speed of sound in the fuel. Therefore, the time required for an acoustic wave pulse to travel to the reflector 26′ (a known distance) and be reflected therefrom and travel to the receiver (a known distance) is measured. The time required for an acoustic wave pulse to travel to and be reflected from the upper surface of the fuel is then measured. The level of the liquid is then accurately determined using the speed of sound in the fuel and the time required for the acoustic wave pulse to travel to and from the upper surface of the fuel. The fuel quantity and density are inferred from information stored in memory 68 about the volume of the tank 12 when filled to several levels and the speed of sound in the fuel and the speed of sound in the fuel determined from the measurement of the time for sound to travel the known distance to and from the reference reflector all as disclosed in above-mentioned US-PS-4 677 305, the disclosure of which is herein incorporated by reference in its entirety.

With more particular reference to Figure 2, an electrically passive opto-acoustic liquid quantity gauging system 110 is shown. The electrically passive acoustic fuel quantity gauging system 110 includes a tank 112 which supports acoustic source 114 and an acoustic detector 116. The acoustic source 114 transmits acoustic output pulses 118 through the portion 120′ of liquid fuel 120 enclosed by stillwell 126 to the liquid-air interface 122 from which acoustic reflection pulses 124 are reflected to acoustic detector 116. The stillwell 126 is supported by the tank 112 so that the pulses 118 and 124 travel through fuel 120′ which is less turbulent in flight than is fuel 120 which is outside of the stillwell 126. Stillwell 126 supports reference reflector 126′. Fuel flows freely into and out of the stillwell 126 through aperture 128.

The source 114 preferably includes a metal member 130 having a rounded or semispherical (concave or convex) shape supported to allow flexion of the rounded portion. Preferably, at least a portion of the surface of the metal member 130 is nonreflective and black. Optical pulser 132 pulses high intensity light through optical fibre 134 to the plate 130 which rapidly flexes thereby transmitting acoustic pulses 118. The pulser 132 is preferably a pulsed laser, pulsed laser diode, Q-switched laser or optically pumped Q-switched laser.

The optical source 136 transmits light through optical fibre 138 to acoustic detector 116. Reflected acoustic pulses 124 impinge upon detector 116. The detector 116 is preferably a loop 140 in optical fibre 138. The fibre 138 may be a single mode or multimode. The output portion 142 of fibre 138 channels the light to optical detector 144. The optical fibre 134, 138 and 142 extend through connectors 139′ and 139″ and are protected by shielding 139. Detector 144 is connected to signal conditioning electronics 146 by electrical conductor 148. Signal conditioning electronics 146 is connected by electrical conductor 150 to high intensity optical pulser 132. Opto-acoustic signal conditioner 158 includes pulser source 136, detector 144 and signal conditioning electronics 146. Signal conditioning electronics 146 includes analog to digital (A/D) converter 160 which is connected by electrical conductor 148 to detector 144, and by electrical conductor 162 to microprocessor 164. Microprocessor 164 sends and receives signals from memory 168 through electrical conductor 166. Microprocessor 164 sends digital signal through conductor 170 to D/A converter 172. D/A converter 172 sends analog signals through electrical conductor 174 to display 176. Power supply 178 supplies electrical current through electrical Conductor 180 to display 176. Power supply 178 supplies electrical current through electrical conductor 182 to optical pulser 132. Power supply 178 is connected through electrical conductor 184 to optical source 136 and through electrical conductor 186 to A/D converter 169.

By detecting and indicating changes in the light signal from the optical source 136, the return of the reflection pulses is detected and used to indicate the quantity of fuel in tank 112. The optical detector 144, which is preferably a photodetector, receives electromagnetic radiation, such as light from the output portion 142 of optical fibre 138. As explained in relation to Figure 1, any type of physical movement of the optical fibre 138, such as slight bending, will have an effect upon the light transmitted therethrough. Various parameters (or properties) of the light can be detected, such as back scattering sites, discontinuities, attenuation, and the like. Such effects on the light in optical fibre 138 result from the physical movement of the reflected acoustic waves which impact on, and result in the movement of, the optical fibre in acoustic detector 116. The optical information is converted to digital form in A/D converter 160 and fed into the microprocessor 164. Fuel quantity

measurement signals from the microprocessor 164 are displayed by display 170. Movement of the acoustic detector 116 is monitored by following the corresponding changes in the parameters of the light passing through the fibre 138, which are detected by optical detector 144 and processed in the microprocessor 164. The microprocessor 164 may send further signals to the optical pulser 132 to control the starting time of the acoustic wave pulses 118.

The metal member 130 in the acoustic source 114 is an optical absorber which absorbs the energy of the light pulses transmitted through the optical fibre 134 to the absorber from the optical pulser 132. The optical energy is converted to heat in the absorber which undergoes a rapid expansion to generate an acoustic wave pulse 118. The wave pulse 118 propagates upwardly to the surface of the liquid and a reflected wave pulse 124 is reflected downward from the liquid-air interface. The acoustic detector 116 (which may be a fibre-optic hydrophone) detects the reflected wave pulse 124. The liquid level is determined as a function of the acoustic pulse propagation time in the manner explained in connection with Fig. 1.

The liquid level may be measured by detecting the change in the intensity of the light transmitted through fibre 138. Instead, the change in the polarization state of the transmitted light is monitored. Another possibility is to use interferometrics.

Tanks in which liquid quantity may be measured using the systems disclose may be made of metal sheeting, polymeric (organic or inorganic), composite or other suitable material. Preferred organic polymeric materials include thermoplastic and thermoset polymers. These materials may include a matrix of metal, for example aluminium, thermoplastic such as polyetherether ketone (PEEK), thermoset polymer or ceramic. A preferred composite structure includes high strength filaments or fibres in a polymeric matrix such as a crosslinked epoxy or maleinide.

Epoxy resins are well established for use in making high performance composite structures which include high strength fibre.

Preferred fibre materials are metal, glass, boron, carbon, graphite, continuous or chopped, or the like, such as disclosed in US-PS-4 656 208 (Chu et al). Structures made of these composites can weigh considerably less than their metal counterparts of equivalent strength and stiffness.

The tanks may be fabricated as disclosed in US-PS-4 581 086 (Gill et al, assigned to Hercules Incorporated). Helical applicators may be used to deposit a ply or plies of continuous filaments into the form of the tank as disclosed in US-PS-4 519 869 (Gill et al, assignee, Hercules Incorporated). Alternatively, multiphase epoxy thermosets having rubber within a disperse phase may be used to make tanks, as disclosed in US-PS-4 680 078 (Bard assigned to Hercules Incorporated). Optical fibres and transceivers may be embedded in or attached to these tanks during fabrication. Attachment to the tanks of the optical fibres transceivers after construction may be carried out using the same or a different matrix material than is used to fabricate the underlying tanks.

Other matrix compositions which may be used to make tanks include poly(aryl-acetylene) as disclosed in US-PS-4 070 333, US-PS-4 097 460, and US-PS-4 144 218. US-PS-4 656 208 discloses thermosetting epoxy resin compositions and thermosets therefrom.

Claims

1. An electro-acoustic transducing arrangement, comprising a movable member (30;130), and characterised by an input device (34;134) directing electromagnetic energy into impingement on the movable member (30;130) whereby to cause the member (30;130) to move and emit acoustic energy, and an output device (16,116) comprising a device (38,42) carrying electromagnetic energy and subject to impingement thereon of the emitted acoustic energy whereby to cause modulation of the carried electromagnetic radiation.

2. An arrangement according to claim 1, characterised by an interposed object (22;122) positioned to receive and affect the emitted acoustic energy whereby the said modulation is a function of the affected acoustic energy.

3. An arrangement according to claim 2, characterised in that the interposed object is the surface (22;122) of liquid (20;120) contained in a tank (12;112) and in that the input and output means devices (34;134;38;42) are fixed in relation to the tank (12;112) whereby the said modulation is a function of the level of the liquid (20;120) in the tank (12;112).

4. An arrangement according to claim 3, characterised by signal processing means (46;146) responsive to the said modulation to produce a corresponding electrical signal and operative in dependence on that electrical signal and on stored information relating to the velocity of acoustic energy within the liquid (20;120) and physical dimension of the tank (12;120) to produce an output corresponding to the quantity of liquid in the tank.

5. An arrangement according to any preceding claim, characterised in that the movable member comprises a flexible member (30;130) adapted to flex when heated, and in that the input electromagnetic radiation is radiation adapted to heat the flexible member (30;130) by impingement thereon.

6. An arrangement according to claim 5, characterised in that the electromagnetic radiation is light or infra-red radiation.

7. An arrangement according to claim 5 or 6, characterised in that the flexible member is a curved thin member (30;130) made of metal and treated to absorb heat.

8. An arrangement according to any preceding claim, characterised in that the input and output devices comprise respective optical fibres (34;134;38;42;138;142) for conducting the electromagnetic radiation.

9. An optically controlled acoustic transmission and reception system, characterised by a tank (12;112) an electrically passive acoustic transmitter (30;130) controlled by electromagnetic radiation, an acoustic receiver (16;116), a source (32;132) of electromagnetic radiation, a first optical fibre (34;134), the first optical fibre (34;134) being connected to transmit electromagnetic radiation from the source (32;132) thereof to the transmitter (30;130) which converts electromagnetic radiation into emitted acoustic energy, the transmitter (30;130) being positioned to emit the acoustic energy into the acoustic receiver (16;116) being positioned to receive the acoustic energy emitted by the transmitter (30;130) and to produce a corresponding output.

10. A system according to claim 9, characterised in that the acoustic receiver (16;116) is electrically passive.

11. A system according to claim 10, characterised in that the acoustic receiver comprises a device (38;42;138;142) for causing modulation of electromagnetic radiation in dependence on the received acoustic energy.

12. A system according to claim 11, characterised in that the electromagnetic radiation which is modulated in dependence on the received acoustic energy is fed to the receiver from an electromagnetic source (36;136) by a second optical fibre (38;138).

13. A system according to any one of claims 9 to 12, characterised in that the tank (12;112) contains liquid (20;120) and in that the acoustic energy (16;116) emitted by the transmitter (30;130) is received by the receiver (16;116) after reflection at the surface (22;122) of the liquid (20;120) and by signal processing circuitry (46;146) responsive to the output from the receiver (16;116) for producing an indication of the quantity of liquid (20;120) in the tank (12;112).

14. A system according to claim 13, characterised in that the liquid is fuel (20;120).

15. A system according to any one of claims 9 to 14, characterised in that the acoustic transmitter comprises a flexible member (30;130) adapted to vibrate and thereby emit acoustic waves in response to impingement thereon of electromagnetic radiation in the first optical fibre (34;134).

16. A system according to any one of claims 9 to 15, characterised in that the electromagnetic radiation is visible light.

17. A system according to any one of claims 9 to 16, characterised in that the electromagnetic radiation is infra-red radiation.

18. A system according to claim 12, characterised in that the electromagnetic radiation in the first optical fibre (34;134) is infra-red radiation and the electromagnetic radiation in the second optical fibre (38;138) is visible light.

19. An acoustic transducing method, characterised by the stePS of impinging electromagnetic radiation on an input movable member (30;130) so as to cause the member (30;130) to move and emit acoustic energy, and causing the emitted acoustic energy to impinge on an output movable member (38;42;138;142) and thereby cause modulation of further electromagnetic energy.

20. A method according to claim 19, characterised in that the impinging electromagnetic radiation is carried by a first optical fibre (34) into impingement with the input movable member (30;130) and the further electromagnetic radiation is carried by a second optical fibre (38;42;138;142) part of which constitutes the output movable member.

21. A method of emitting acoustic waves into a liquid (20;120) enclosed by a tank (12;112), characterised by the step of feeding electromagnetic radiation through an optical fibre (34;134) into impingement on a flexible member (30;130) mounted within the liquid (20;120) so as to vibrate in response thereto and emit acoustic waves into the liquid (20;120).

22. A method according to claim 21, characterised by the steps of detecting the acoustic waves reflected from the surface (22;122) of the liquid (20;120) to produce a resultant output signal, and determining from the output signal the quantity of liquid (20;120) in the tank (12;112) in dependence upon the time of travel of the acoustic waves to and from the liquid surface (22;122) the predetermined speed of transmission of acoustic waves within the liquid (20;112) and dimensions of the tank (12;122).

23. A method according to claim 22, characterised in that the step of detecting the reflected acoustic waves comprises the step of passing further electromagnetic radiation through a movable member (38;42;138;142) positioned to receive the reflected acoustic waves which cause corresponding modulation of the electromagnetic radiation.

24. A method according to any one of claims 19 to 23, characterised in that the impinging and/or the further electromagnetic radiation is visible light.

25. A method according to any one of claims 19 to 23, characterised in that the impinging and/or the further electromagnetic radiation is infra-red radiation.

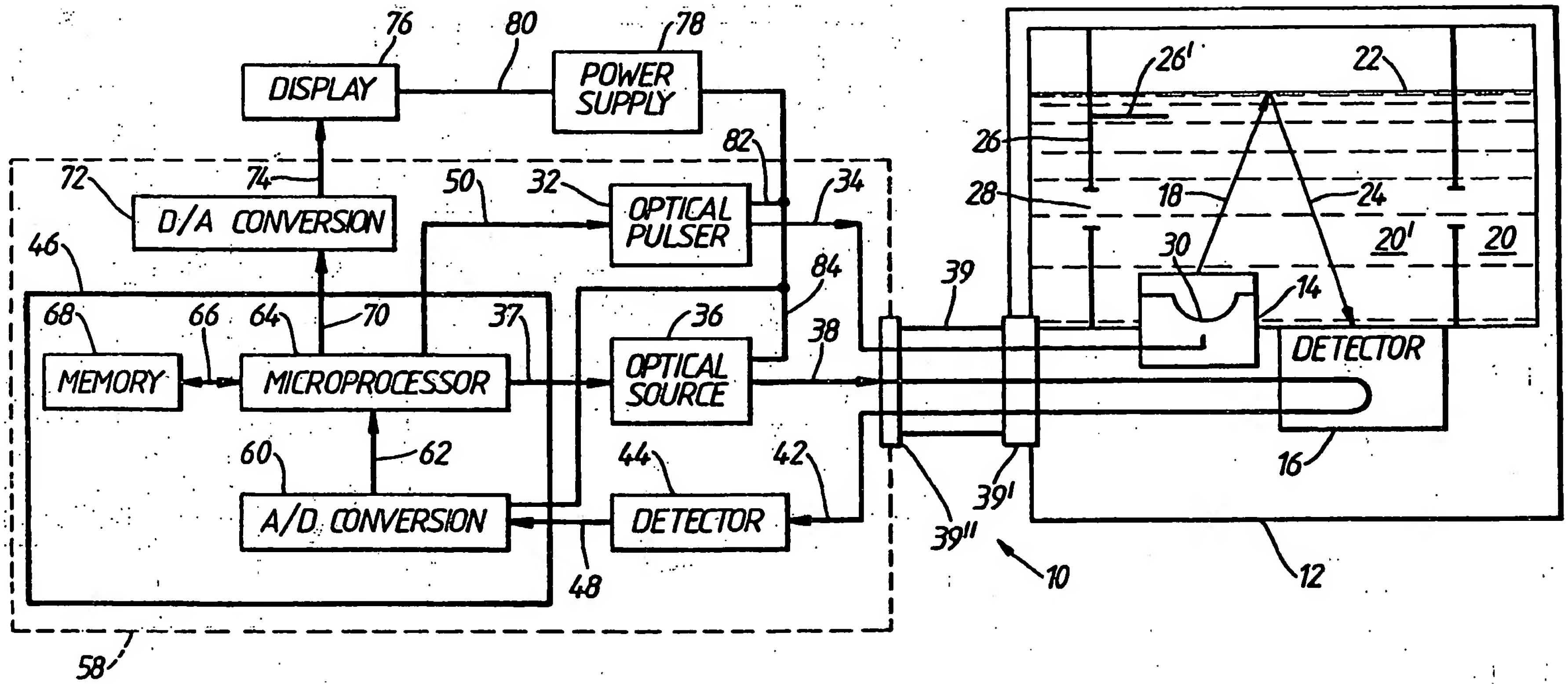
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Fig.1.

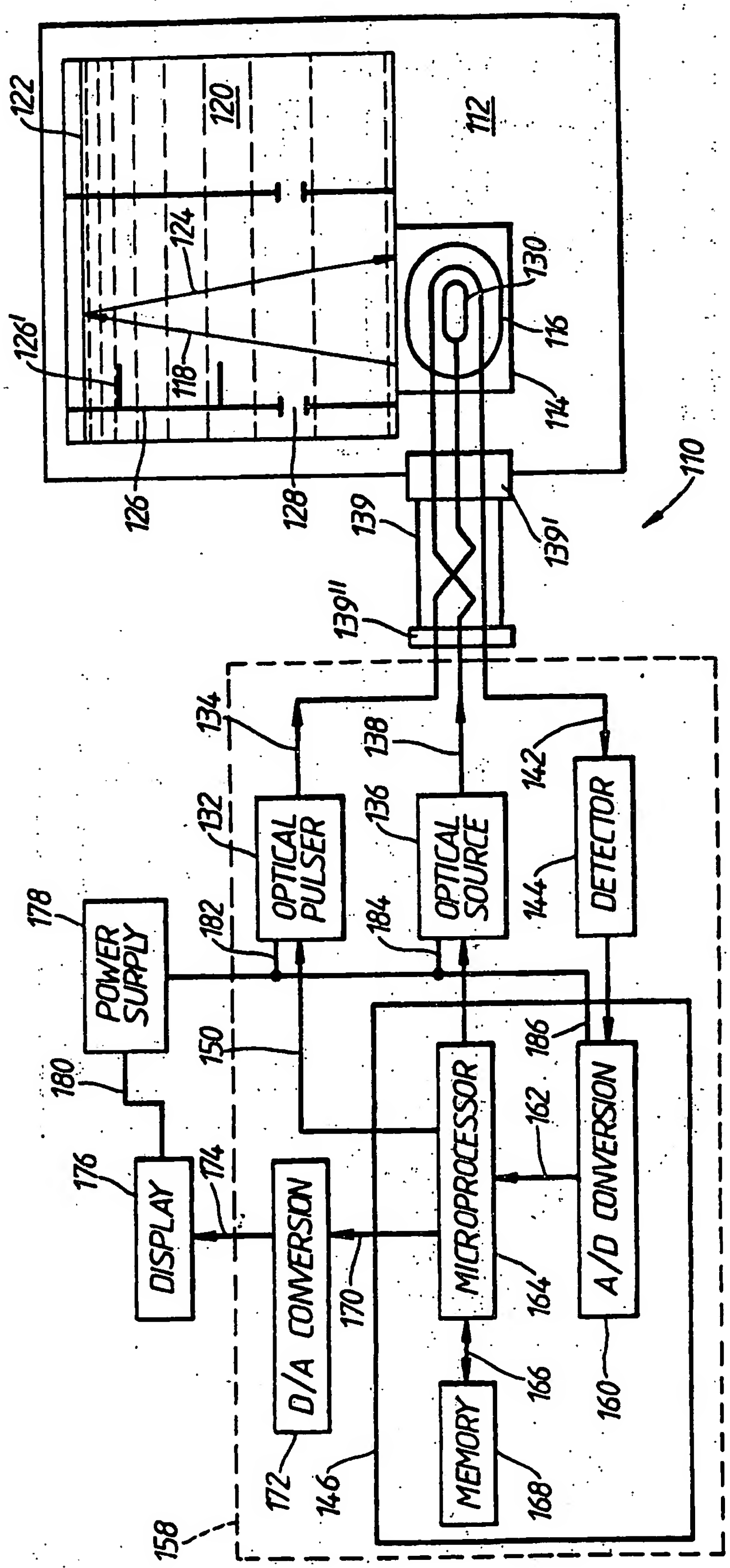
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Fig.2